Update of the LHC Higgs WG 1 VH subgroup: experimental & theory status

H. Arnold (Nikhef), A. Calandri (ETH Zürich), G. Ferrera (Milan U.), C. Williams (Buffalo U.)
on behalf of the LHC Higgs WG 1 VH subgroup

The 19th Workshop of the LHC Higgs Working Group

November 29, 2022

Overview of VH subgroup activities in 2022

Nikhef

[Link](#)

November 2022

22 Nov WG1 - VH subgroup

October 2022

10 Oct WG1 - VH subgroup

May 2022

12 May WG1 - VH subgroup

February 2022

03 Feb WG1 Updated Higgs Cross Sections

[VH subgroup twiki](#)

- Full Run-2 **VH, H→bb** results in ATLAS & CMS - focus: signal/background modelling
- "fall meeting" on recent **theoretical developments** on VH(→bb) and gluon-initiated ZH
- Full Run-2 **VH, H→cc** results in ATLAS & CMS - focus: signal/background modelling
- First, interpolated cross-sections at 13.6 TeV for Run 3

[Link](#)

WG1 Higgs XS&BR parallel: Morning 2 — 503/1-001 - C

11:00 Exact top-quark mass dependence in hadronic Higgs production
Speaker: Mr Marco Niggetiedt

VH subgroup

11:30 V+jets background modeling in CMS
Speaker: Aliya Nigamova (University of Hamburg (DE))

11:50 V+jets background modeling in ATLAS
Speaker: Maria Mironova (Lawrence Berkeley National Lab. (US))

12:15 ggZH 0+1J studies in ATLAS
Speaker: Philipp Windischhofer (University of Chicago (US))

Follow-up from discussions on VH, H→bb/cc results

gg→ZH @ATLAS

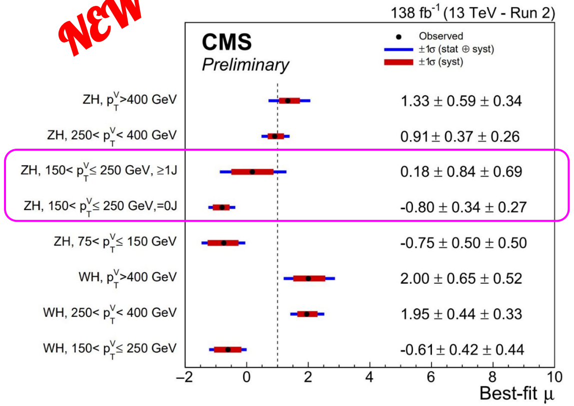
This talk: summary of what we learned in those discussions and next steps

Run-2 VH(→bb) STXS results - state-of-the-art

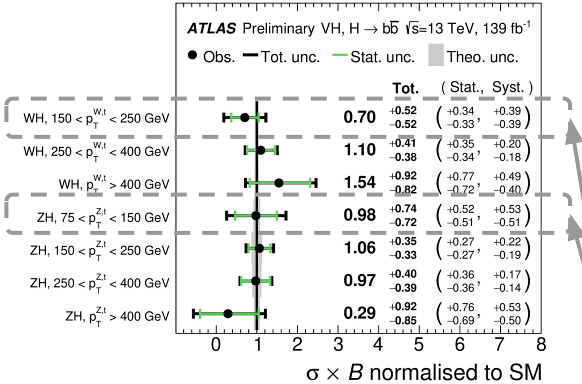
Nikhef

NEW

CMS-PAS-HIG-20-001

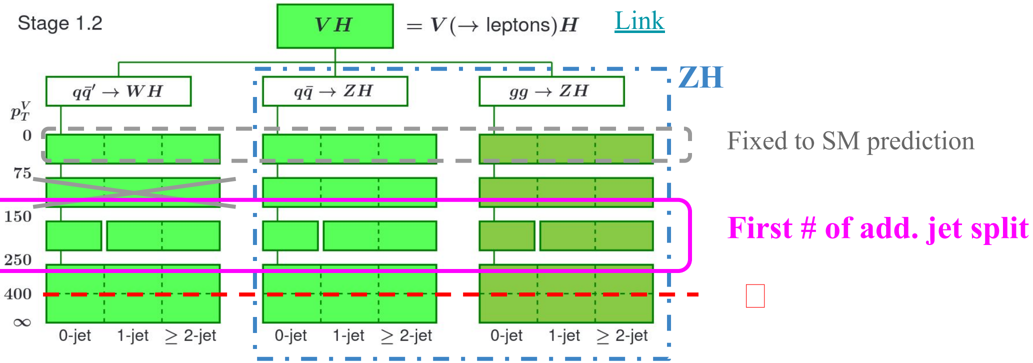


ATLAS-CONF-2021-051



VH, H→bb allows the most granular STXS measurement in VH

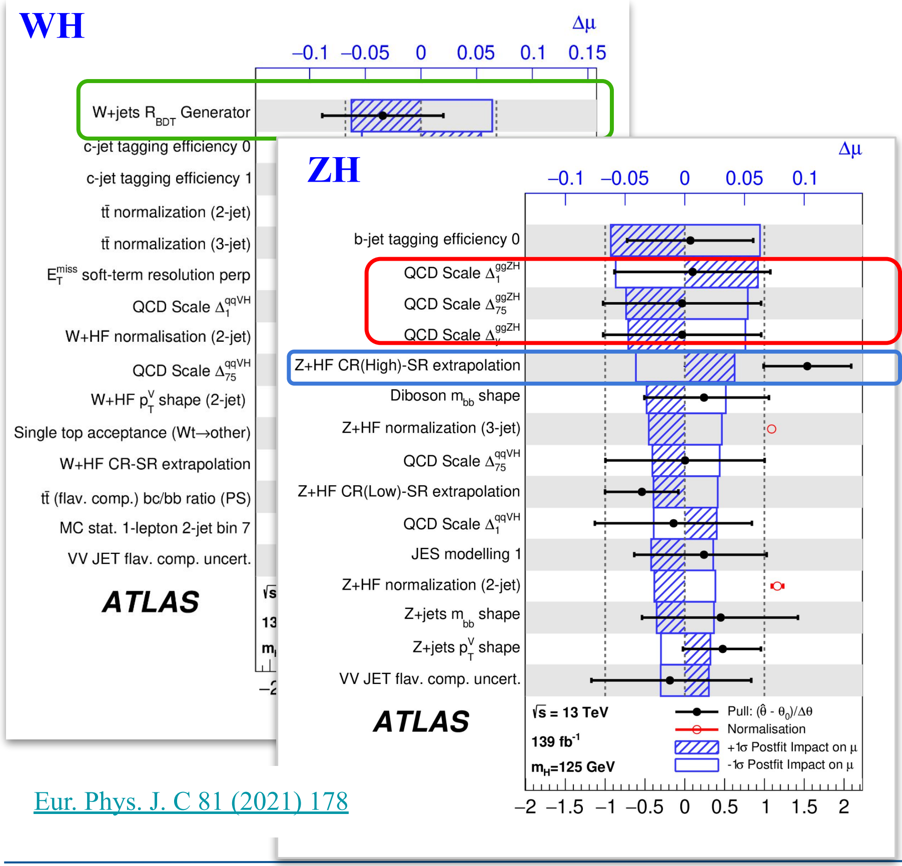
- 4 (3) STXS ZH (WH) measurements in pTV
- **First ZH STXS measurement in # of add. jet** for 150 GeV< pTV < 250 GeV by CMS
- ≳ 1 s.d. exp. sensitivity in each category



- With increasing data samples, signal and background modelling becomes more challenging and more important
  - Signals are extracted in profile-likelihood fits with systematic uncertainties as nuisance parameters
- (Modelling) systematic uncertainties start to become dominant

Run-2 VH(→bb): systematic uncertainties

Nikhef



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Theory/modelling uncertainties have a strong impact on the VH signal extraction, especially

- **VH signal** uncertainties
- **V(W/Z)+heavy-flavour jets** modelling
  (+ limited simulated sample sizes)

VH CMS-PAS-HIG-20-001

	$\Delta\,\mu$
Background (theory)	+0.067 −0.064
Signal (theory)	+0.082 −0.060
MC stats.	+0.092 −0.093
Sim. modelling	+0.070 −0.066
b tagging	+0.059 −0.041
Jet energy resolution	+0.045 −0.057
Luminosity	+0.041 −0.034
Jet energy scale	+0.029 −0.036
LeptonID	+0.016 −0.002
Trigger(MET)	+0.001 −0.001

Dominated by V+jets

Run-2 VH(→bb): V+jets modelling

Nikhef

V(W/Z)+heavy-flavour jets main, irreducible background

Modelling strategy:

- Initial estimates from **simulations**
- Determine **normalisations** of V+hf-jets components in final fit from data with the help of dedicated **control regions**
  - low/high dR(bb) or m(bb) regions
- Assign **uncertainties** on the estimates from simulation

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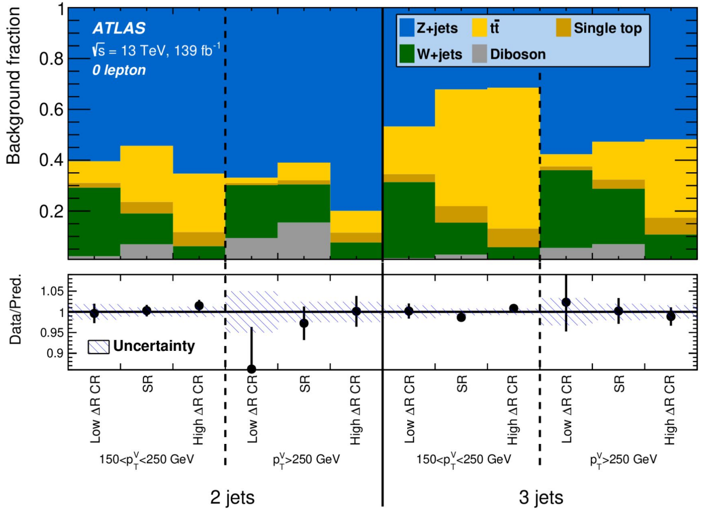


General strategy very *similar* in ATLAS/CMS, details *quite different*

⇒ currently comparisons are not straightforward

V+jets modelling: simulated samples

Nikhef

ATLAS

- **Sherpa 2.2.1** 5FS (0-2 jet @NLO, 3-4 jet @LO)
- XSec: reweighted to NNLO in QCD
- Outlook:
  - **Nom.: Sherpa 2.2.11** 5FS (0-2 jet @NLO, 3-**5** jet @LO) (& 4FS V+bb) incl. NLO EWK corr.
  - Alt.: MadGraph5_aMC@NLO **at NLO** w\ FxFx merging

CMS

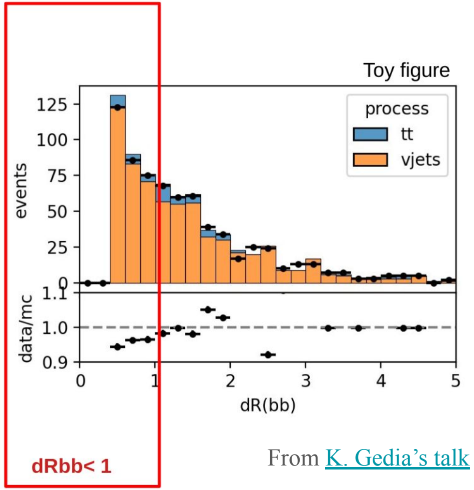
- **2016:** MadGraph5_aMC@NLO **at LO** w\ MLM matching
  + *reweighting* to NLO in dEta(bb) (from simulation)
- **2017/** MadGraph5_aMC@NLO **at NLO** w\ FxFx merging
  2018 + *reweighting* of dR(bb) using control-region data
- XSec: reweighted to NNLO in QCD & **NLO EWK in pTV**

NEW

⇒ Can we agree on at least one common sample for better comparability in the future? Prepare document a la `ttbar+hf modelling for ttH` [PUB note]?

dR(bb) mismodelling & correction

NEW

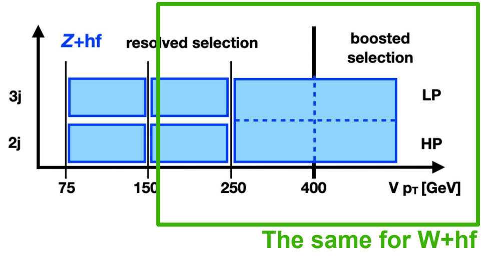


From K. Gedia's talk

- Mismodelling jet-flavour agnostic → correction from V+light-jet control region
  - per lepton channel and reco pTV bin
- Associated systematic unc.

Run-2 VH(→bb): V+jets floating normalisations

ATLAS



- **Individual normalisations per region** determined from data where possible (pTV, # of jets)
- **Coherent between channels:** 0/2L (Z) and 0/1L (W)

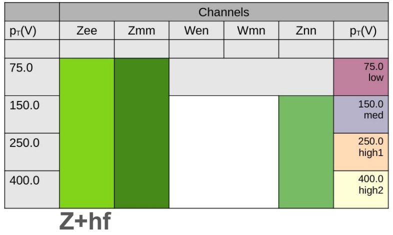
ATLAS-CONF-2021-051

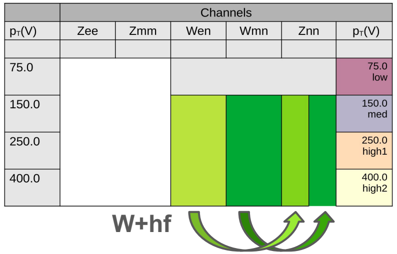
Process and category	Normalisation factor
W+hf 2-jet, 150 GeV $< p_T^V <$ 250 GeV	1.11 ± 0.12
W+hf 3-jet, 150 GeV $< p_T^V <$ 250 GeV	1.16 ± 0.10
W+hf $p_T^V >$ 250 GeV	1.10 ± 0.10
Z+hf 2-jet, 75 GeV $< p_T^V <$ 150 GeV	1.28 ± 0.08
Z+hf 3-jet, 75 GeV $< p_T^V <$ 150 GeV	1.17 ± 0.05
Z+hf 2-jet, 150 GeV $< p_T^V <$ 250 GeV	1.19 ± 0.07
Z+hf 3-jet, 150 GeV $< p_T^V <$ 250 GeV	1.11 ± 0.05
Z+hf $p_T^V >$ 250 GeV	1.07 ± 0.05

- 10-20% differences between Sherpa prediction and data

CMS

From K. Gedia's talk





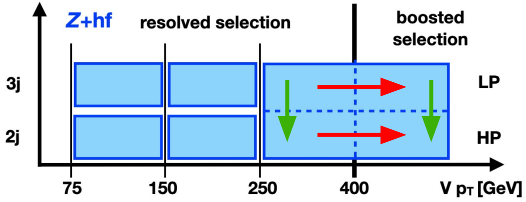
- **Individual normalisations per lepton flavour and year**
  - Z: 0L, 2L *ee*- and 2L *μμ*-channels
  - W: 1L *e*- and 1L *μ*-channels
    - Avg. applied to 0L channel
  - The different data taking years
- **Correlated across pTV and # of jets categories**

⇒ Can we harmonise the strategies?

V+jets modelling: systematic uncertainties

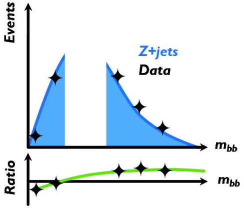
ATLAS

- **Sources:** PDF and renormalisation/factorisation scale variations, **alternative generator** (MG5_aMC@NLO **at LO**+Pythia8)
- **Acceptance / extrapolation unc.** between analysis regions with common norms.: **pTV**, **# of jets**, **CR →SR**, 1/2L→0L for W/Z+jets, flavour composition,...
  - Prior: quadrature sum of different sources

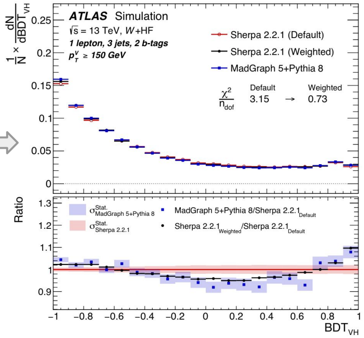


"Analysis dimension rather than input source" V. Dao

- **Shape uncertainties**,
  - mainly nom. vs alt. generator
  - 1D (pTV, mJ,..) or multi-D ⇨
  - exception:



W+jets R_{BDT} generator (1. rank)



From M. Mironova's talk

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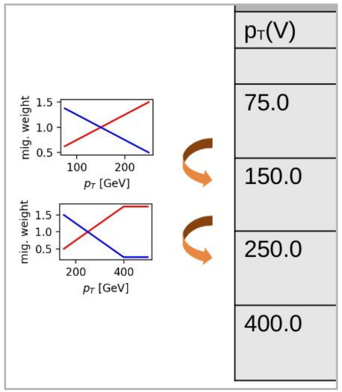
CMS

- **Sources:** PDF; renorm./fact. scale variations

⇒ Correlated *normalisation* + *shape* effects across all analysis regions

NEW

- **Add. acceptance unc.** across some **pTV** categories
  - Flat, ad hoc prior unc. ⟶



- **Add. shape uncs.** from
  - dEta(bb) reweighting
  - dR(bb) correction

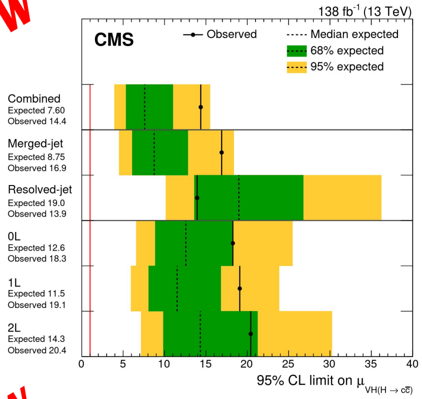
From K. Gedia's talk

⇒ Can we harmonise?

Intermezzo: Run-2 VH(→cc)

NEW

CMS-HIG-21-008



NEW

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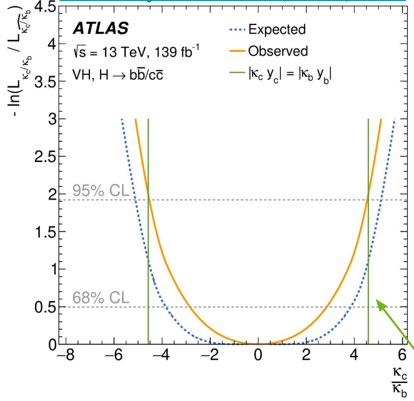


Strongest limit on VH, H→cc production to date

- Result dominated by merged-jet category
- Result statistically limited

V+jets modelling approach/issues/… similar to VH(bb) (in resolved regime)

More difficult because of diverse flavour composition

Combination with VH, H→bb analysis

⇒ **experimental confirmation that Higgs-charm coupling is weaker than Higgs-bottom coupling**

- Statistical and systematic unc. of similar sizes

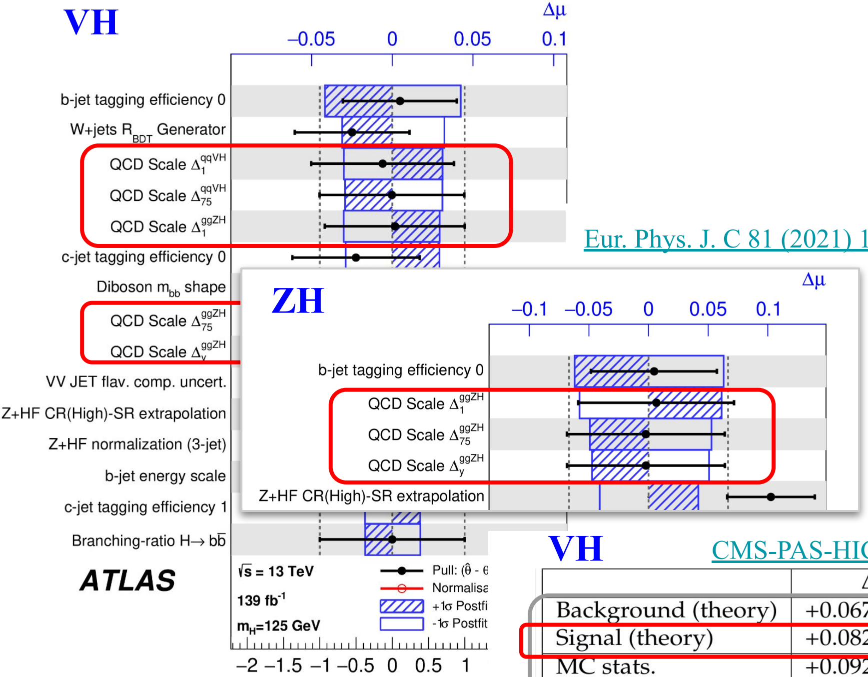
Value at which Higgs coupling to b- and c-quarks is equal (m_b/m_c)

Uncertainty source	$\Delta\mu/(\Delta\mu)_{tot}$
Statistical	**85%**
Background normalizations	37%
Experimental	**48%**
Sizes of the simulated samples	37%
c jet identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Integrated luminosity	6%
Lepton identification efficiencies	4%
Theory	**22%**
Backgrounds	17%
Signal	15%

Source of uncertainty		$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total		15.3	0.24	0.48
Statistical		10.0	0.11	0.32
Systematic		11.5	0.21	0.36
Statistical uncertainties				
Signal normalisation		7.8	0.05	0.23
Other normalisations		5.1	0.09	0.22
Theoretical and modelling uncertainties				
$VH(\to c\bar{c})$		2.1	< 0.01	0.01
Z+jets		7.0	0.05	0.17
Top quark		3.9	0.13	0.09
W+jets		3.0	0.05	0.11
Diboson		1.0	0.09	0.12
$VH(\to b\bar{b})$		0.8	< 0.01	0.01
Multi-jet		1.0	0.03	0.02
Simulation samples size		4.2	0.09	0.13
Experimental uncertainties				
Jets		2.8	0.06	0.13
Leptons		0.5	0.01	0.01
E_T^{miss}		0.2	0.01	0.01
Pile-up and luminosity		0.3	0.01	0.01
Flavour tagging	c-jets	1.6	0.05	0.16
	b-jets	1.1	0.01	0.03
	light-jets	0.4	0.01	0.06
	τ-jets	0.3	0.01	0.04
Truth-flavour tagging	ΔR correction	3.3	0.03	0.10
	Residual non-closure	1.7	0.03	0.10

Dominant!

Run-2 VH(→bb)$^{(*)}$: signal modelling



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VH

CMS-PAS-HIG-20-001

	Δ μ
Background (theory)	+0.067 −0.064
Signal (theory)	+0.082 −0.060
MC stats.	+0.092 −0.093
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Jet energy resolution	+0.045 −0.057
Luminosity	+0.041 −0.034
Jet energy scale	+0.029 −0.036
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Trigger(MET)	+0.001 −0.001

$^{(*)}$For VH, H→cc, the same samples are used and systematic unc. sources considered.

Signal samples

- **qq → VH**: Powheg v2 + MiNLO + Pythia8 (NLO)
  + NLO EWK corr. as function of pTV (HAWK)
- **gg → ZH:** Powheg v2 + Pythia8 (LO)

STXS uncertainty scheme following ATL-PHYS-PUB-2018-035

Sources:

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	Signal
Cross-section (scale)	0.7% (qq), 25% (gg)
$H \to b\bar{b}$ branching fraction	1.7%
Scale variations in STXS bins	3.0%–3.9% ($qq \to WH$), 6.7%–12% ($qq \to ZH$), 37%–100% ($gg \to ZH$)
PS/UE variations in STXS bins	1%–5% for $qq \to VH$, 5%–20% for $gg \to ZH$
PDF+α_S variations in STXS bins	1.8%–2.2% ($qq \to WH$), 1.4%–1.7% ($qq \to ZH$), 2.9%–3.3% ($gg \to ZH$)
m_{bb} from scale variations	M+S ($qq \to VH$, $gg \to ZH$)
m_{bb} from PS/UE variations	M+S
m_{bb} from PDF+α_S variations	M+S
p_T^V from NLO EW correction	M+S

ATLAS only

- Pythia8 tune unc.
- **Alternative parton shower** (Herwig7)

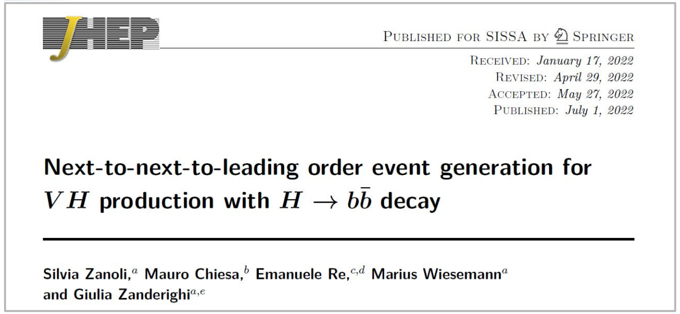
Significant impact of (gg→ ZH) signal acceptance unc. on VH (ZH) measurement

NEW

Recent theory development: qq→VH

Nikhef

JHEP07 (2022) 008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Published: July 1, 2022

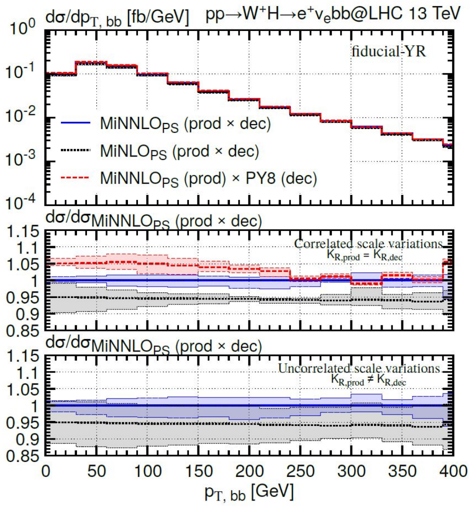
Next-to-next-to-leading order event generation for VH production with $H \to b\bar{b}$ decay

Silvia Zanoli,[a] Mauro Chiesa,[b] Emanuele Re,[c,d] Marius Wiesemann[a] and Giulia Zanderighi[a,e]

Cross-section predictions

- Inclusive XSec in **good agreement with the NNLO predictions** from vh@nnlo
- Relative to MiNLO':
  - **5-6% upward corrections**
  - **Significantly reduced scale unc.**

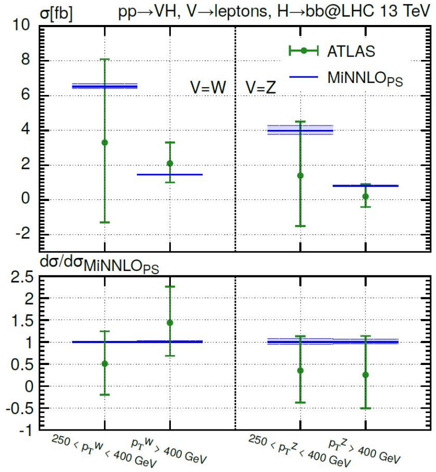
Also in differential distributions



some accidental cancellations in the scale variations

NNLO+PS accuracy for VH production *and* H→bb decay

- **For qq→WH achieved for the first time!**



Good agreement with data

⇒ Test in ATLAS and CMS

Approach:

- MiNNLO$_{PS}$ in production
- NNLOPS in decay
- Shower (Pythia8) consistently matched

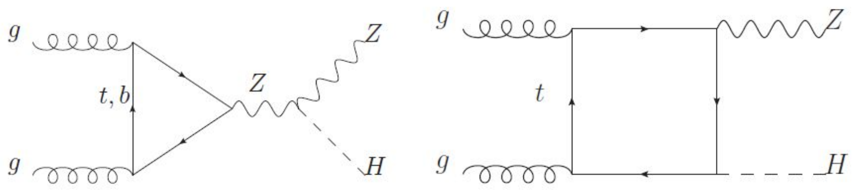
MiNNLO$_{PS}$ evaluates NNLO corrections on-the-fly

NNLOPS = MiNLO' + fully differential reweighting to NNLO

⇒ MiNNLO$_{PS}$ avoids computationally intense reweighting

NNLOPS predictions valid ⇒ validation

Why is gg→ZH important?

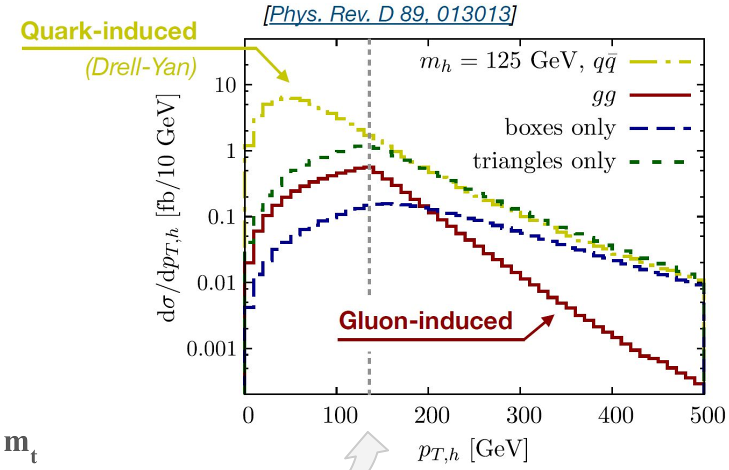


@LO: one loop diagrams - NNLO correction to qq→ ZH

⇒ loop suppression vs large gluon luminosity
⇒ contributes **~6% to the total cross section; significant around pTH ~ m_t**

- **Only LO included in MC (see before)**
  ⇒ large scale variations: ~25%

- **NLO corrections expected to be large**



From P. Windischhofer's talk

⇒ gg→ZH @ NLO important to improve the prediction & associated uncertainties for ZH measurements

Recent theory developments: gg→ZH (1)

(*)Together with
PLB 829 (2022) 137087
"small-mass expansion"

Nikhef

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On the NLO QCD corrections to gluon-initiated ZH production

Giuseppe Degrassi,[a,b] Ramona Gröber,[c] Marco Vitti[b] and Xiaoran Zhao[b]

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Published: August 3, 2022

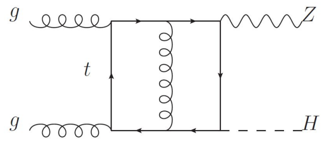
ZH production in gluon fusion at NLO in QCD

Long Chen,[a,i] Joshua Davies,[b] Gudrun Heinrich,[c] Stephen P. Jones,[d] Matthias Kerner,[c,e] Go Mishima,[f] Johannes Schlenk[g] and Matthias Steinhauser[h]

Full NLO results(*) - different strategies of merging existing approaches to address *NLO virtual corrections*,

in particular, two-loop boxes with multiple scales (m_t, m_H, m_Z,...)

⇐ cannot be computed analytically with current loop techniques



"pT expansion" - expansion of small transverse momentum of final state particles (first applied to gg → HH)

"Numerical evaluation" using *sector decomposition*

\+

\+ real emissions: RECOLA2 / MadGraph5

Analytic approximation:
"high-energy (and large m_t) expansion"
supplemented with Padé approximants

\+ real emissions: GoSam + in-house C++ code

NEW

Recent theory developments: gg→ZH (2)

(*)Together with [PLB 829 (2022) 137087](#) "small-mass expansion"

Nikhef

[JHEP 08 (2022) 009](#)

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Inclusive cross section results

Top-mass scheme	LO [fb]	$\sigma_{LO}/\sigma_{LO}^{OS}$	NLO [fb]	$\sigma_{NLO}/\sigma_{NLO}^{OS}$	$K = \sigma_{NLO}/\sigma_{LO}$
On-Shell	$64.01^{+27.2\%}_{-20.3\%}$	—	$118.6^{+16.7\%}_{-14.1\%}$	—	1.85
$\overline{\text{MS}}, \mu_t = M_{ZH}/4$	$59.40^{+27.1\%}_{-20.2\%}$	0.928	$113.3^{+17.4\%}_{-14.5\%}$	0.955	1.91
$\overline{\text{MS}}, \mu_t = m_t^{\overline{\text{MS}}}(m_t^{\overline{\text{MS}}})$	$57.95^{+26.9\%}_{-20.1\%}$	0.905	$111.7^{+17.7\%}_{-14.6\%}$	0.942	1.93
$\overline{\text{MS}}, \mu_t = M_{ZH}/2$	$54.22^{+26.8\%}_{-20.0\%}$	0.847	$107.9^{+18.4\%}_{-15.0\%}$	0.910	1.99
$\overline{\text{MS}}, \mu_t = M_{ZH}$	$49.23^{+26.6\%}_{-19.9\%}$	0.769	$103.3^{+19.6\%}_{-15.6\%}$	0.871	2.10

$\mu_R = \mu_F = M_{ZH}/2$

$\sqrt{s}$	LO [fb]	NLO [fb]
13 TeV	$52.42^{+25.5\%}_{-19.3\%}$	$103.8(3)^{+16.4\%}_{-13.9\%}$
13.6 TeV	$58.06^{+25.1\%}_{-19.0\%}$	$114.7(3)^{+16.2\%}_{-13.7\%}$
14 TeV	$61.96^{+24.9\%}_{-18.9\%}$	$122.2(3)^{+16.1\%}_{-13.6\%}$

$\mu_R = \mu_F = M_{ZH}$

- In agreement with each other (and (*)) within scale uncs.
- **NLO corrections: ~ x2 LO contribution**
- **Scale unc. significantly reduced: ~-30-40%**

XSec currently used by ATLAS&CMS are close (NLO corrections obtained in the $m_t \to \infty$ limit + soft-gluon effects at NLL)

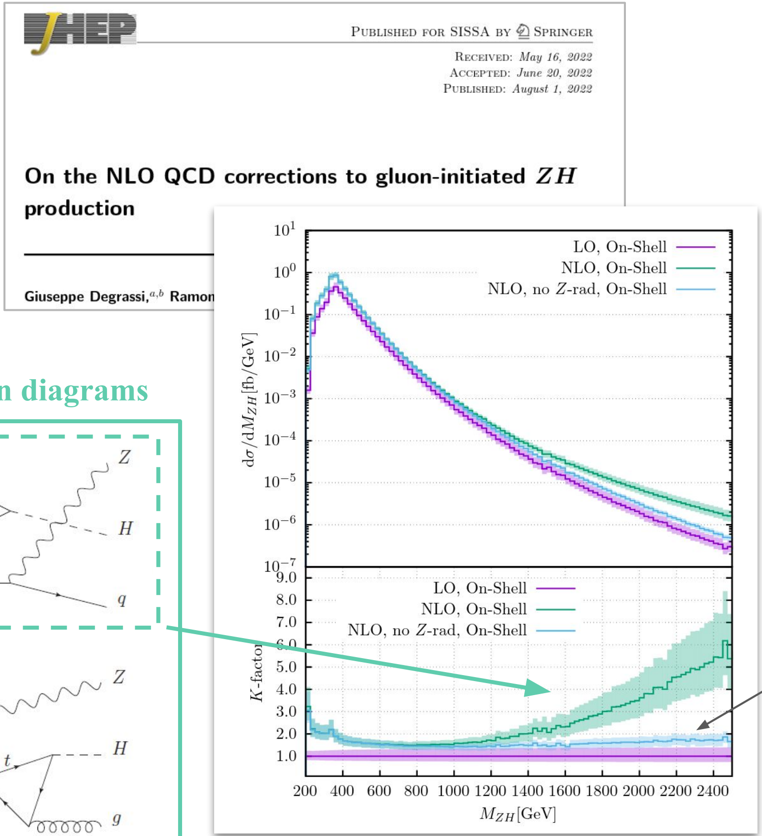
NEW

Recent theory developments: gg→ZH (3)

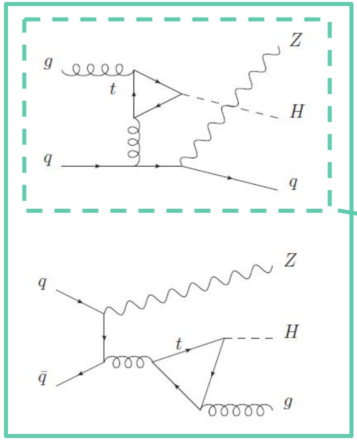
(*)Together with
[PLB 829 (2022) 137087](PLB 829 (2022) 137087)
"small-mass expansion"

Nikhef

JHEP 08 (2022) 009



Z-radiation diagrams



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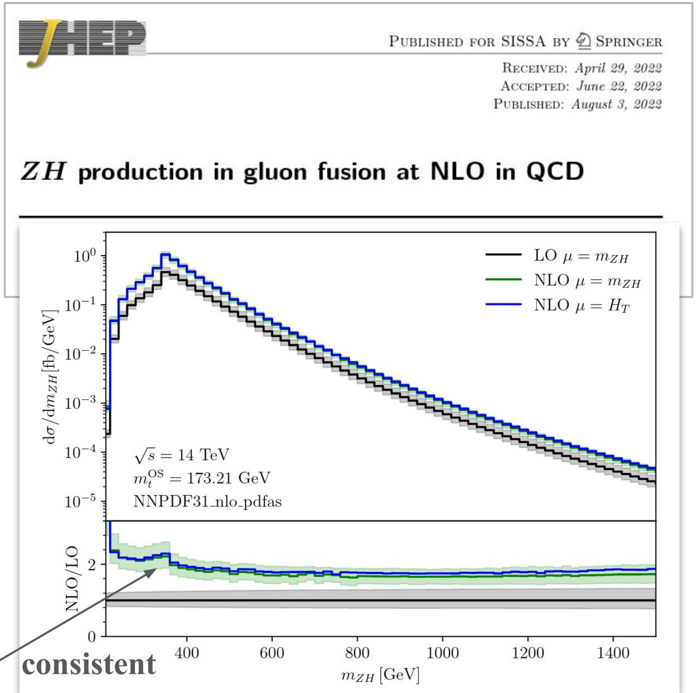

Real emission Z-radiation diagrams *excluded*
⇒ no enhancement at high mZH observed

NEW

Recent theory developments: gg→ZH (4)

(*)Together with PLB 829 (2022) 137087 "small-mass expansion"

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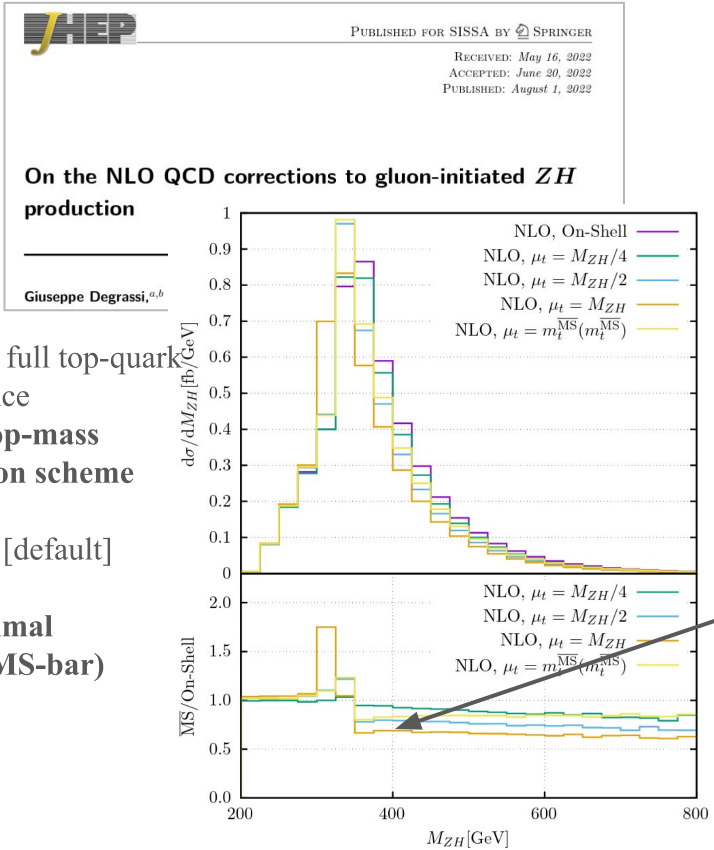

Strategies with full top-quark mass dependence
⇒ impact of **top-mass renormalization scheme**

On-shell (OS) [default]
vs
modified Minimal Subtraction (MS-bar)

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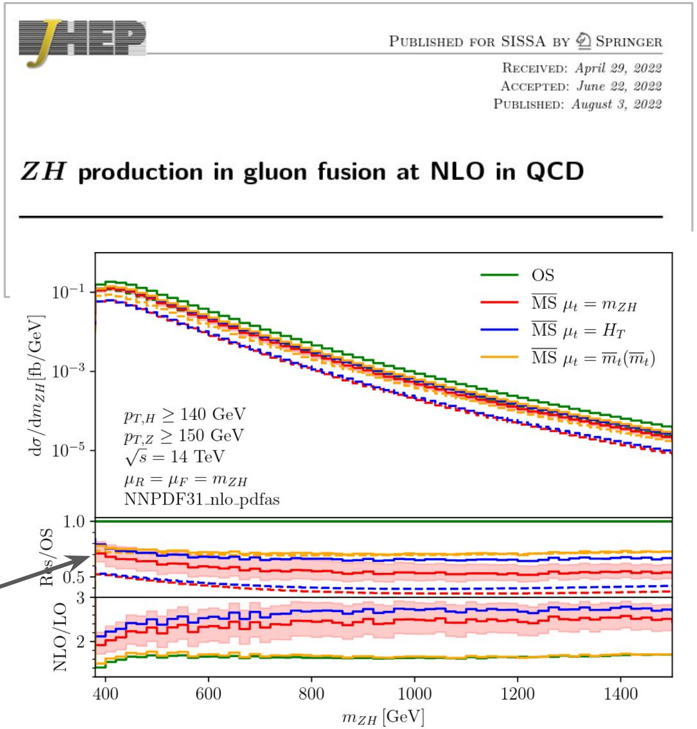

Dashed line: LO

MS-bar consistently lower

NEW

Recent theory developments: gg→ZH (5)

(*)Together with PLB 829 (2022) 137087 "small-mass expansion"

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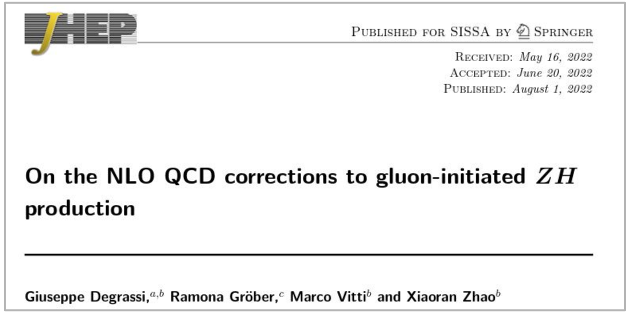
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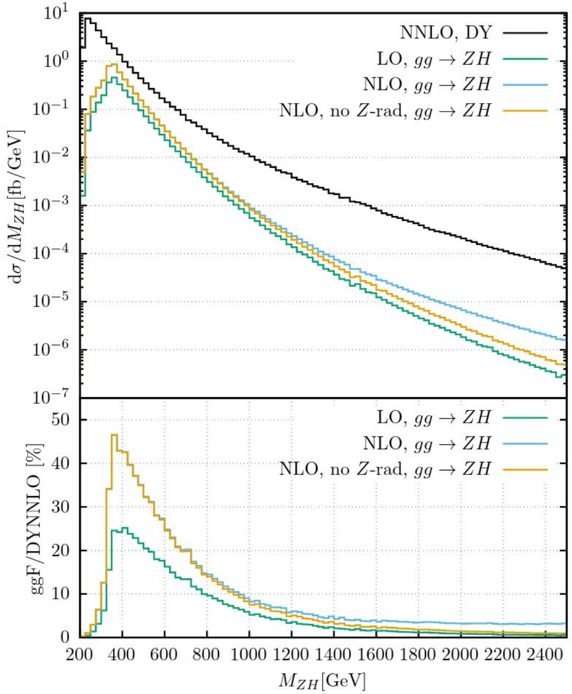
On the NLO QCD corrections to gluon-initiated ZH production

Giuseppe Degrassi,[a,b] Ramona Gröber,[c] Marco Vitti[b] and Xiaoran Zhao[b]



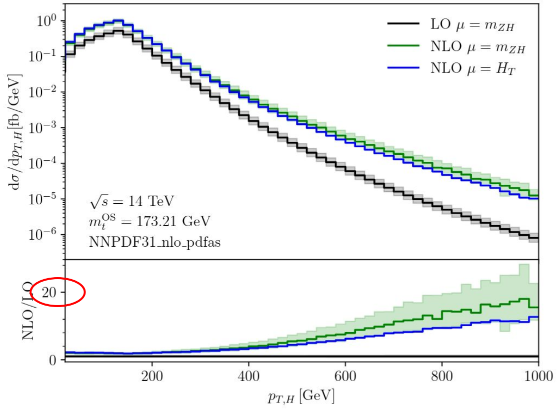
gg→ZH almost 50% of Drell-Yan qq → ZH near $2m_t$

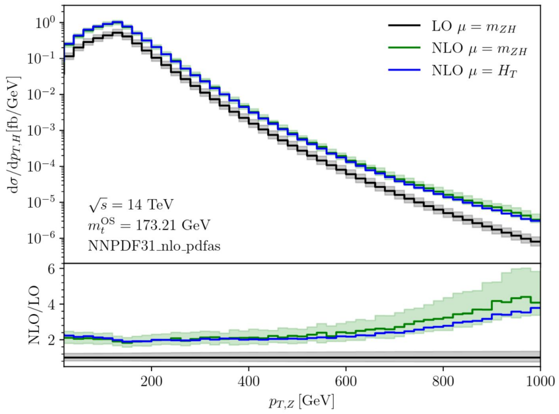
NEW

Recent theory developments: gg→ZH (6)

(*)Together with
PLB 829 (2022) 137087
"small-mass expansion"

Nikhef





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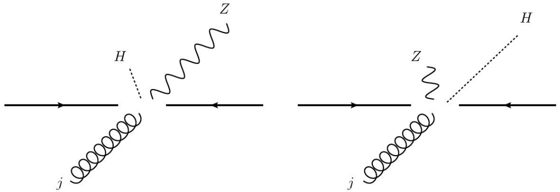
ZH production in gluon fusion at NLO in QCD

Long Chen,[a,i] Joshua Davies,[b] Gudrun Heinrich,[c] Stephen P. Jones,[d]
Matthias Kerner,[c,e] Go Mishima,[f] Johannes Schlenk[g] and Matthias Steinhauser[h]



Large enhancement at high pT

- Higgs recoiling against a hard jet more likely
- Effect reduced by pT cuts

$p_{T,H} \geq 140$ GeV
$p_{T,Z} \geq 150$ GeV

Observed before in JHEP06 (2015) 065 and Les Houches study (arXiv:2003.01700) [0+1j@LO]

NEW

Recent theory developments: gg→ZH (7)

(*)Together with PLB 829 (2022) 137087 "small-mass expansion"

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⇒ Next step: unified prediction with the same diagrams included and setups used - thanks a lot!

NEW

Loop-induced ZH @ATLAS

ATL-PHYS-PUB-2022-055

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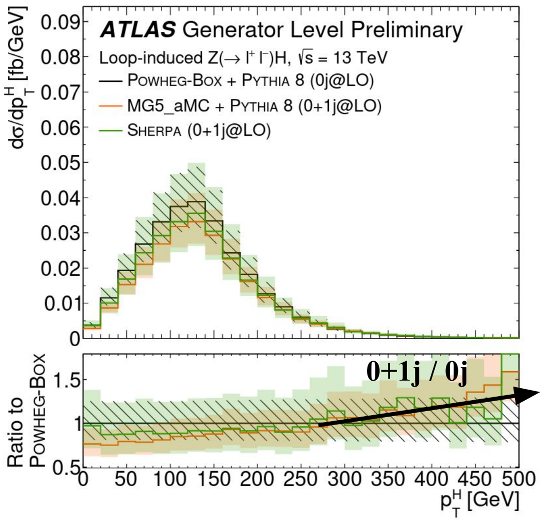
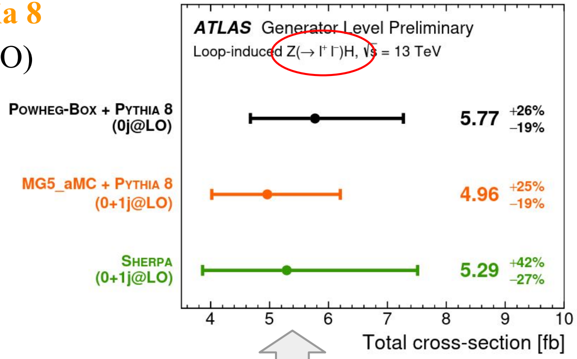
Comparison of two ME+PS predictions of **loop-induced ZH with up to one additional jet (0+1j@LO)**:

- **Sherpa**
- **MadGraph5_aMC@NLO+Pythia 8**

to current default Powheg+Pythia8 (0j@LO)



Similar **enhancement at high pTH** as seen by M. Kerner et. al. and Les Houches study



In agreement with each other and LO calculations within scale uncs.

Impact of scale choice in MG:

Default: $\mu_R = \mu_F = M_T$- after k_T-like clustering

Alternative: $\mu_R = \mu_F = M_T/2$

➡ $7.03^{+27\%}_{-20\%}$

⇒ **+42% - significantly larger than individual scale variations**

Uncertainty from scale variations significantly larger for Sherpa than MG5_aMC and PP8 (~40% vs ~25%)

⇒ **Overestimated/underestimated?**

⇒ **Understand scale-choice dependence**

⇒ **Replace PP8 with MG5_aMC (also in CMS?)**

Summary

Nikhef

- **Several fruitful meetings** over the past year related to
  - Signal and background modelling in full-Run 2 VH(→bb/cc) analyses
  - Recent theory developments regarding signal predictions, in particular loop-induced ZH

- (Modelling) systematic uncertainties start to become dominant source of uncertainty in some STXS bins
  ⇒ important to keep improving both on theory and experimental side (e.g. how theory developments used in analyses)

- **Better understanding of the (different) modelling approaches in ATLAS and CMS VH(bb/cc) analyses**
  - Summary for essential V+jets background modelling yesterday
  - Plan to follow-up further and try to harmonise: agree on at least one common sample, document comparison,...

- **NNLO+PS accuracy for ZH/WH production *and* H→bb decay via MiNNLO$_{\mathbf{PS}}$** ⇒ Follow-up in ATLAS/CMS

- **Three independent full NLO gg→ZH calculations** ⇒ <u>next step</u>: unified predictions

- **Step towards improved gg →ZH modelling in ATLAS: 0+1j@LO samples**
  - ToDo: understand scale-choice dependence of MadGraph5_aMC@NLO+Pythia8
  - Adopt as new default sample?